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A Conceptual Framework to Design Green Infrastructure: Ecosystem Services as an Opportunity for Creating Shared Value in Ground Photovoltaic Systems

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Abstract: This paper presents a conceptual framework that looks at photovoltaic systems in synergy with ecosystem services. The focus is to connect business success with social and ecological progress based on the operative concept of multifunctional land use. Such an approach attempts to harmonise the needs of the industrial processes of photovoltaic systems and the ecological and social needs of the landscape context. Different from the usual design of ground photovoltaic systems in farmlands or brownfields, a new framework is proposed, combining photovoltaic panels and vegetation. A case study is considered, applying the framework to existing photovoltaic systems in the Apulia region (southern Italy). The analysis shows how the framework has, among others, the major functions of increasing solar energy production, recycling wastewater, creating raw material for biofuel, as well as providing animal habitat and mitigating air temperature. The latter is preliminarily evaluated by means of modelling simulations performed with a computational fluid dynamics and microclimate model, ENVI-met. This approach opens up a new vision of the infrastructure design of photovoltaic systems which can produce new social and economic income.

Keywords: ground photovoltaic system; land use; ecosystem services; green infrastructure; water treatment and supply; multifunctional land use; technology services; creating shared value

1. Introduction

Land-use change due to human activities has generally been considered a local environmental issue, but it is becoming a force of global importance [1–3] as it has negative effects on the global carbon cycle and climate change [4] through changes in surface energy and water balance [5,6]. In fact, land-use change, in fact, may cause biodiversity decline through habitat loss, modification and fragmentation and overexploitation of native species, compromising ecological functions important for the wellbeing of present and future generations [7–13]. Chasing the goal of a shift to a decarbonised economic growth, specific European policies (Directive 2001/77/CE) push towards the development of renewable energies, indirectly driving a process of deep landscape and land-use transformation. Electricity generation through ground photovoltaic (GPV) systems is regarded as a feasible solution to reduce greenhouse gas emissions [14–19] However, the realisation of GPV systems requires the remodelling of suitable areas with severe impacts on landscapes and ecosystems [14–19]. Currently, the design of GPV systems produces a loss of agricultural lands with a primary focus on the optimisation of panel positioning in the space available ("full space"), with little or no emphasis on the space around or between panels ("pore space") [20,21]. In this sense, the energy sector is expected to be the main driver of the land-use change, limiting alternative uses of the land [22,23]. Thus, energy policies have created the paradox that the actions aimed at reducing greenhouse gas emissions and mitigating global warming are likely to cause local aberrations of land use and landscape. This can have potentially negative effects on climate change and human wellbeing [1,4,21].

Strategic decisions, policies and actions aimed at limiting human intervention within the carrying capacity of ecosystems, preserving their vitality and resilience and maintaining the capacity to provide goods and services in the long-term, are thus required [24]. Mainly, it is necessary to stimulate the inclusion of the ecosystem services concept in energy project design that represents the human benefits derived from the combination of biophysical structures and ecological functions [25], supporting the sustainable development goals of cities [26]. Ecosystem services are not intrinsic aspects of the GPV design, making it is necessary to stimulate the energy companies to include them by developing a link with business economic income and without the provision of incentives that could produce inefficient results or undesirable solutions [27]. Only the full awareness of the application of ecological solutions within a process of land-use transformations can produce technological progress and productivity growth, increasing efficiency in the use of natural resources and pushing the companies to adopt them. The ecological solution has to develop appropriate ecosystem services to connect the companies' production processes and meet human needs in the context of the reference [11,28–30].

In this context, an important focus for energy projects that imply land-use change is producing new landscape elements, such as green infrastructure (GI), that are promoted by European Union (EU) policy for both rural and urban areas (EC, 2013). GI has been defined as "...a strategically planned network of natural and seminatural areas with other environmental features designed and managed to deliver a wide range of ecosystem services..." [31]. In urban contexts, GI can be seen as a built ecosystem integrated with artificial and hybrid infrastructures that are able to provide a wide range of ecosystem services, such as water purification, air quality, space for recreation and climate mitigation and adaptation [13,21,32,33]. Several activities compete for the same space (e.g., infrastructure, agriculture, energy production, recreation) and multifunctional land use represents an approach that is instrumental in combining several activities on the same area. This approach, coupled with appropriate landscape design solutions, is conceived as a strategy that, besides supporting primary functions (i.e., food, fibres and other production), provides secondary services to the community, such as biodiversity conservation, support for socioeconomic activities of rural areas, improved flood mitigation, and the quality and safety of production [34–39]. This is coherent with the indications of the EU Biodiversity Strategy for 2030, promoting "win–win solutions for energy generation" like solar-panel farms that provide biodiversity-friendly soil cover [40].

Scognamiglio [41], with a critical review, proposed the idea that GPV systems should be designed as an element of the landscape they belong to, according to an "inclusive" design approach focusing on the overall energy efficiency of the system and other additional ecological and landscape objectives. Therefore, it is important to emphasise the solution that involves nature's contributions to people at the landscape scale and the company scale in the business processes. In recent years, different works have attempted to develop multifunctional land use connected to GPV systems by trying to use the space below the panels for grazing, harvesting, biodiversity implementations, or biking [41–44]. Currently, developing solutions in the agrophotovoltaic sector are based on approaches aimed at using arable land areas to produce food and to generate PV electricity at the same time [45–47]. In this way, agrophotovoltaic solutions increase land-use efficiency and enable GPV capacity, while still retaining fertile arable areas for agriculture. This approach is mainly focused on ecosystem services related to food production, thus representing a good solution to reduce social and economic conflicts between energy production and agricultural activities [48–51]. However, this solution has to consider the simultaneous impacts of agricultural activities and GPV systems on landscape value since they could produce negative effects, such as excessive monoculture, use of pesticides, and the introduction of invasive species, which produce important ecosystem services loss, such as a decline in pollination and biodiversity [52–56]. Moreover, these projects mainly aim to increase the use of the space in GPV systems with solutions not directly connected to the improvement of energy production: for example, an ecological solution could be to reduce the temperature around the GPV panels, thus increasing energy production and producing additional income [57]. In this direction, the hybrid photovoltaic green roof is a new frontier in the green roof industry since it helps to improve electrical yield [58]. The vegetation can mitigate the surrounding temperature of the PV panels, and the PV panels can reduce sun exposure by the vegetation. Many scholars have estimated the increase of energy efficiency of PV green roofs from a minimum of 1.3% to a maximum of 8.3% with respect to the traditional systems [59]. Therefore, it can be used as sustainable building practices for the sustainable city [60]. These initiatives have not been widely spread in the construction of GPV systems; currently, the new solutions involve more complex plant management, with no direct economic returns for the company. On the contrary, this type of projects constitutes an additional cost for the business [20,21]. The GI design integrated into GPVs has to consider the added value that the ecosystem services can generate for business productivity.

An important point in this direction is a transition toward a new energy project that is able to develop significant feedback between business strategies that use environmental resources, including land-use and corporate social responsibility. This should create new ways to achieve economic success in creating shared value (CSV) [29,61]. CSV represents a corporate policy and practice that enhances the competitive advantage and profitability of the company, while simultaneously advancing social and economic conditions in the communities in which it sells and operates [62]. In businesses that produce land-use change, a significant challenge of CSV is accounting for ecosystem services in the e-commerce model to produce positive (environmental) externalities within the economic system and in the social–ecological context. Therefore, the ecosystem services developed have to create a strong link between different needs of the companies and public interest, stimulating local cluster development to support ecological, social, and economic needs, opening a new market and new income opportunities.

An example in this sense is the installation of floating PV systems on water bodies (oceans, lakes, lagoons, dams, and canals). This is an appealing option, acknowledged as beneficial for several reasons, including the possibility of avoiding additional land use for PVs and the increase in energy productivity due to water reflectance (albedo). Currently, this technology is being applied in many artificial basins. However, the design of the basin and the PVs occurs separately and without integration, thereby limiting the use of these basins for other purposes [63]. In all these applications, photovoltaics is conceived as a layer of an energy-related infrastructure that overlaps an existing "traditional" infrastructural layer. However, many times, these solutions become a simple sum of elements that are not thought of synergistically in the plant design phase and without considering the social and ecological benefits that can be produced in the area. A separation between energy planning and landscape design still exists, with the consequence that on a large-scale, specific landscape, the features requiring careful attention are instead overlooked during project implementation [23].

In this context, the aim of this paper is the development of a conceptual framework of land-use design aimed at reducing economic and social–ecological conflict and creating a synergy between business needs and ecosystem services production. Therefore, this paper promotes green infrastructure in GPV systems that, starting from identifying the needs and requirements of current and future human populations, can establish the most appropriate natural solutions, with mutual benefit for populations and businesses.

In the next sections, we present the conceptual framework of the paper applied to the context of the Apulia region in southern Italy, where there has been significant land-use change driven by energy production. In this context, we analyse the social, ecological, and economic needs, at both the regional level and in the context of some GPV systems used as specific case studies, in which the development of GI can be detailed. We also develop a potential GI solution to improve specific direct and indirect ecosystem services to CSV for socioeconomic and ecological benefits and potential benefits for energy companies. Finally, we discuss the implications of the solution proposed and the design of the applied conceptual framework.

2. The GPV System Conceived as Green Infrastructure

In this sense, GPV system fields are designed as engineered ecosystems that can mimic "natural ecosystems" in providing direct ecosystem services, such as gas regulation, climate regulation, wastewater treatment, freshwater supply and, indirectly, raw material. GI is set to represent biodiversity sink and stepping stones to support animal movement in ecological networks [64].

In this work, we try to develop logic reasoning connecting the four main questions:

- What are the landscape needs we want to address? It is important to identify and focus on the ecological, social and economic target needs of the reference context.
- What are the ecosystem services linked to these problems? It is necessary to focus on the type of ecosystem services, biophysical structures and ecological functions that can satisfy the human and business needs identified.
- What are the potential solutions? It is necessary to think about technical solutions when developing GI to support the priority ecosystem services.
- Why do we choose these solutions? It is useful to identify all ecosystem services, other than the priorities, that can be developed and the benefits they can produce for human wellbeing and the potential additional income for businesses.

Figure 1 shows the conceptual framework proposed to build human activities that produce land-use changes integrated with the ecosystem and allow economic, ecological, and social aspects to coexist, creating trade-off and synergy among them [20,51,65].

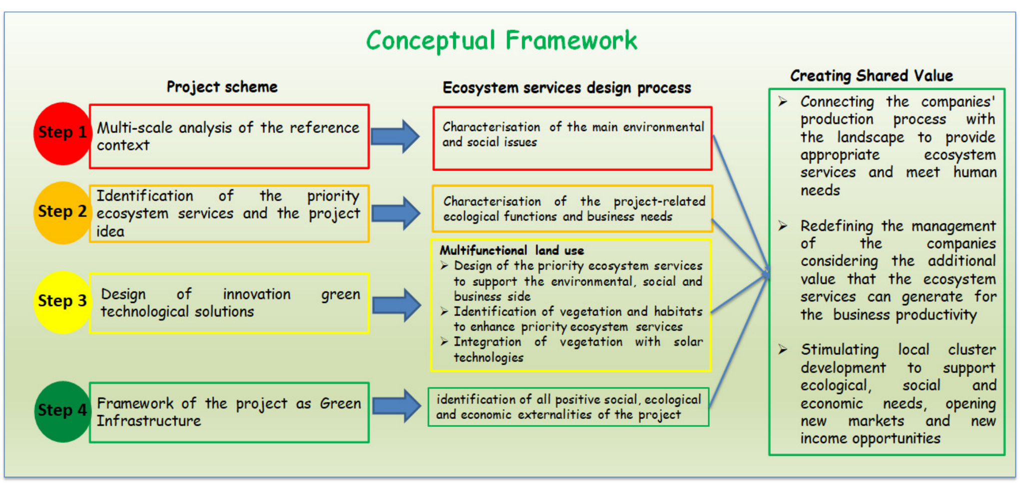

Figure 1. The proposed conceptual framework shows a design workflow in human activities producing land-use change that is useful to build green infrastructure supporting priority ecosystem services production and improving the business processes driving the land-use change.

In the field of GPV systems, the proposed framework adopts a new multifunctional land-use approach in designing and assessing GPV systems integrating "full and pore spaces" to help reduce environmental impacts and offering novel opportunities for ecosystem services [41].

The idea is to design a new spatial arrangement of GPV panels and vegetation in a synergic way with habitats or ecosystems that is useful for developing ecological functions and supporting the ecological, social, and economic needs of the context of the reference and, at the same time, improving business energy processes. Specifically, starting from the analysis of already existing plants, the spatial pattern of GPV systems is based on design strategies that are able to increase the ecological functions of the "pore space" and also the space under the photovoltaic panels to guarantee greater efficiency in land use.

This new approach shifts from a "passive vegetation development in GPV systems" that incurs management cost for frequent mowing to prevent panel shading and fires to an "active vegetation or ecosystem design" that plans specific vegetation to produce ecosystem services and additional economic income. It is expected that this "green design" may increase energy production and, at the same time, enhance the social–ecological value of the areas, creating an infrastructure that is not the sum of two infrastructures that provide two different services but a single element capable of offering both services with mutual benefits.

3. Practical Application of the Framework to a Case Study

The proposed framework is based on several steps presented and discussed in the following subsections, taking into consideration a real case study in the Apulia region (southern Italy). Following Figure 1, the main points considered for the ecological design are

- Step 1. Identification of the social, ecological and economic needs between GPV systems and the context of reference, including the landscape issues analysis on the regional level about GPV systems, considering the present vegetation types and the relationship existing between "pore space" and full space in the same GPV systems.
- Step 2. Identification of the priority ecosystem services and the main biophysical structures and ecological functions that we want to develop in the design of the GPV systems as GI.
- Step 3. Indication of the pattern relationship and interaction between vegetation that is able to produce specific ecosystem services and panel technology (height above the ground, distance between the panels): characterisation of the activities carried out to reduce the risk of fire and shading of the panels due to uncontrolled vegetation growth.
- Step 4. Indication of the social–ecological and potential business benefits: characterisation of all the variations of ecosystem services that can be supported with the GI solutions and potential economic income.

3.1. Step 1. Multiscale Analysis

In this step, the environmental issues useful to identify the priority ecosystem services that the GI solution has to develop are analysed. Specifically, Section 3.1.1 analyses the social, ecological and economic issues at a regional scale where the GI will be set. Section 3.1.2 analyses the main characteristics of some GPV systems that are useful to set specific solutions to introducing constructed habitats to support priority ecosystem services integrated to GPV systems.

3.1.1. Characterisation of the Ecological and Social Issues in the Apulia Region

One of the major problems in the future will arguably be the availability of water for human needs [66]. The areas most affected by the water crisis (Figure 2) will be where there is a high concentration of solar irradiance, which makes these areas extremely appropriate for the installation of GPV systems [67–69].

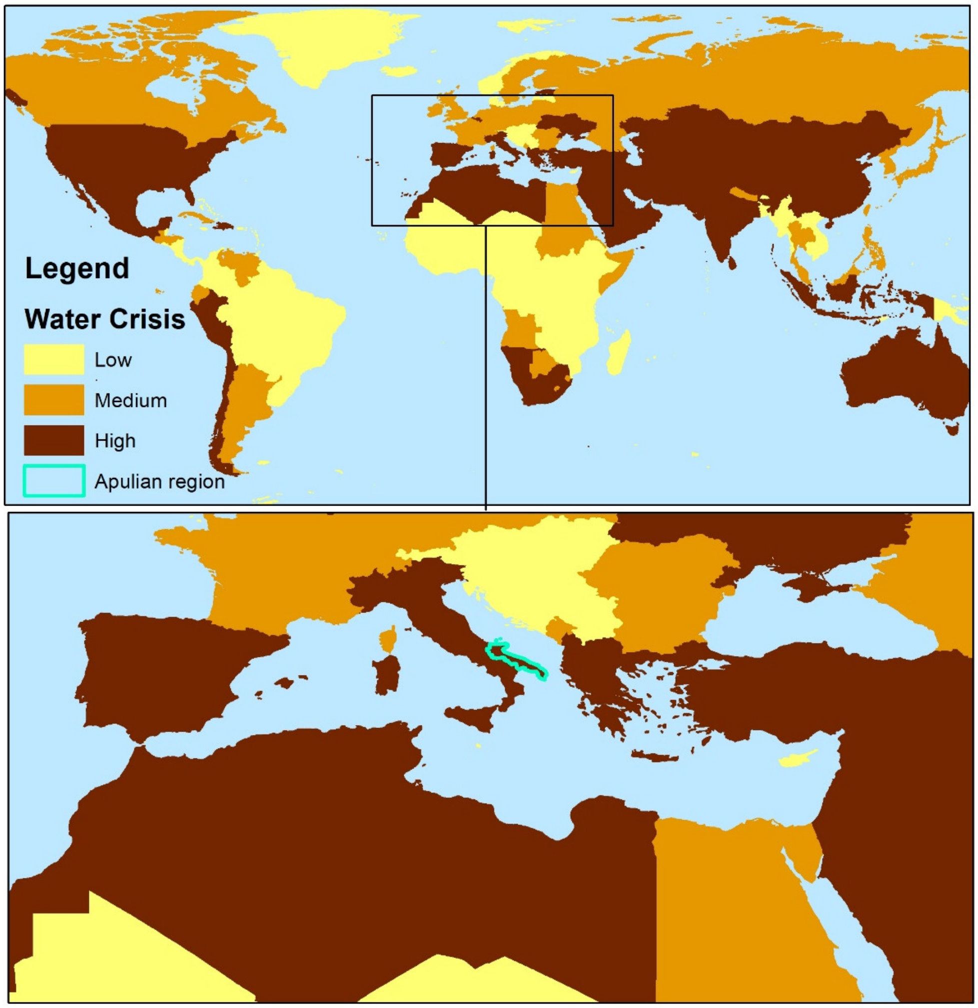

Figure 2. The world spatial analysis of the water crisis in future years. Data sources from [66].

Some of these areas can be defined as socioecological systems where the landscape has been strongly transformed by anthropic activities and where there is a strong interaction between social, economic and ecological aspects [70]. A representative case of these conditions can be found in the Apulia region. The Apulia region has become a privileged scene in which to observe and study the full-scale competition for land use between agriculture and renewable energy production. This is due to its optimal environmental characteristics, such as high solar irradiance, which guarantee high productivity of electrical energy from renewable sources. Moreover, the presence of a large flat surface, with slopes of less than 15%, makes this territory geomorphologically suitable for the installation of GPV systems.

For this reason, many fields have been converted to GPV electricity generation, thanks to national and regional legislation, which have favoured the installation of renewable energy production. Nowadays, the region has more installed GPV capacity than any other region in Italy, and in 2015, it reached the national record in terms of installed power, with 2600 MW [71].

Besides suffering from strong fragmentation and loss of agricultural land, the agricultural sector in Apulia is subjected to severe water scarcity. The regional surface and groundwater supply are stressed by increasing demand, runoff decline and deep percolation. The problem of the exploitation of water resources becomes central during the summer when the presence of many tourists increases water consumption. Therefore, the local water management agency (AQP) sometimes decreases pipeline pressure to cut the delivery of potable water intended for residential use [72,73]. This also causes sewage treatment issues. Indeed, the wastewater treatment plants, designed and sized to fulfil the needs of the local population, often fail to meet the increased requirements during the summer season.

The agricultural sector is often characterised by excessive use of monoculture, mainly olive groves of 457,228 ha (24% of the total surfaces) and arable lands of 777,171 ha (40% of the total surfaces). Together, these represent 64% of the surface of the Apulia region and a high fragmentation of farms, which have led to a severe loss of biodiversity and the associated ecosystem functions. Indeed, the natural area characterised by "forest and shrubs", "grasslands", "water bodies" and "wetlands" represents only 18% of total surfaces of the Apulia region. "Wetlands", in particular, have the residual area of 2092 ha in the region (Table 1). Figure 3 shows the map of main land-use and GPV systems located in the Apulia region in the year 2016, localised and digitalised using an available orthophoto of 2016 from a webGIS application [74]. As known and widely reported in the literature [41], GPV systems always generate the same "unintentional" landscape, characterised by a repetition of rows of panels oriented east–west and exposed to the south, with all dimensional features optimised for maximising energy generation while reducing land use. In terms of energy production (with no attention to any ecological issue), this pattern is the most cost-effective. The total land occupied by main GPV systems is 5388 ha and land-use change is mainly characterised by a 3780-ha surface subtracted from the arable lands that represent 70% of the total area occupied by GPV systems (Table 1).

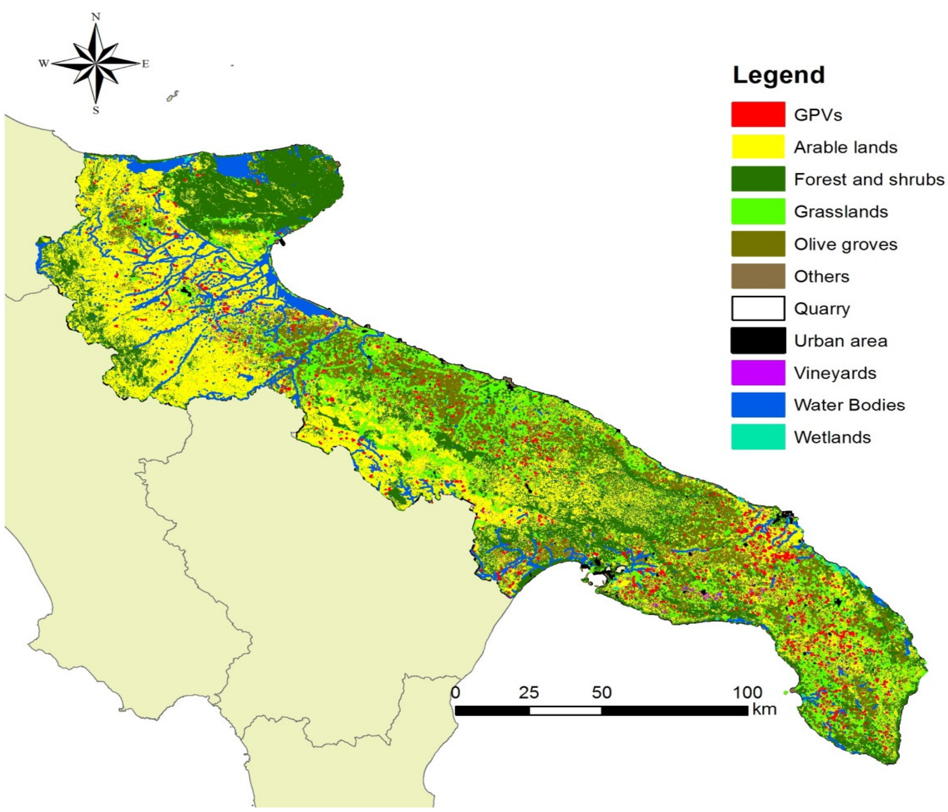

Figure 3. GPV systems realised until 2016 and land use in the Apulia region. Land use data sources from [74].

Table 1. The main land use of the Apulia region and loss of land use caused by the realisation of ground photovoltaic (GPV) systems.

Land-Use Classification	Land Use in the Apulia Region in 2011		Land Use Loss for GPVs in 2016	
	ha	%	ha	%
Arable lands	777,171	40	3780	70%
Forest and shrubs	190,424	10	0	0

Grasslands	128,931	7	199	4%
Olive groves	457,228	24	330	6%
Others	63,353	3	234	5%
Quarry	7524	0	261	5%
Urban areas	146,371	8	0	0
Vineyards	137,205	7	584	11%
Water bodies	22,571	1	0	0
Wetlands	2092	0	0	0
Total	1,932,869	100	5388	100%

3.1.2. Characterisation of "Pore Spaces" and "Full Spaces" in GPV Systems

Using the orthophoto, some examples of the GPV systems showing a high percentage of free surface land with respect to the area occupied by the photovoltaic panels installed were selected. The aim is to estimate the efficiency in land use. Some of the GPV systems are located near the urban areas and have a portion of pore space higher than 40% of the full space of the GPV systems. The minimum dimension (full space) of the GPV system analysed is 2.2 ha and the pore space has a dimension from 1.0 to 30.1 ha. In this context, the main loss of agricultural typology is arable lands and vineyards (Figure 4 and Table 2).

Figure 4. Characterisation of pore spaces in some GPV systems (**A**–**L**) located in the Apulia region (southern Italy), in the provinces of Brindisi and Lecce. Please see Table 2 for the description of the systems.

Table 2. The surface (ha) of the pore space and full space in GPV systems reported in Figure 4.

GPV Systems	Pore Space (ha)	Panels (ha)	Full Space	Pore Space/Full Space	Land Use Loss
A	1.72	1	2.72	63%	Arable lands
B	1.8	2.3	4.1	44%	Arable lands
C	3.6	2.9	6.5	55%	Arable lands
D1	1.3	1.4	2.7	48%	Arable land and vineyards
D2	1.9	1	2.9	66%	
D3	1.6	1.2	2.8	57%	
E	30.1	30.2	60.3	50%	Arable land and vineyards
F	3.9	4.4	8.3	47	Arable land and vineyards
G	11.1	9.7	20.8	53%	Arable lands
H	1.9	1.1	3.0	63%	Arable land
I	1.0	1.3	2.2	41%	Arable lands and olive groves
L	1.8	1.6	3.6	53%	Vineyards

Visual inspections showed that pore spaces and GPV panels are surrounded by ruderal herbaceous vegetation with low capacity to support ecosystem services [20,75]. The ruderal vegetation characterises land exploited for human activities. This situation can characterise the GPVs, where there is land occupation with no planning or direct management of the vegetation growing around and above the panels [76]. This situation may be found again in phytogeographical areas like those found in the Apulia region.

3.2. Step 2. Identification of the Priority Ecosystem Services and the Project Idea

Considering the local need to improve the availability of water and wastewater treatment, a high level of pore space in GPV systems with scarce ecological function and human use, and the need of energy companies to reduce the temperature around the GPV panels, the idea is to replace the ruderal vegetation that grows mainly in the pore spaces, as a result of human disturbances, with a habitat that is able to support priority ecosystem services such as water supply, wastewater treatment, microclimate regulation and biodiversity support. In this specific case, the proposal consists of the replacement of herbaceous vegetation with constructed treatment wetlands (CTWs). CTWs can be considered appropriate GI since, even if they are essentially wastewater treatment systems, they can also, directly and indirectly, support biodiversity and human wellbeing by providing several valuable wetland ecosystem services [77,78]. Indeed, CTWs are engineered wetland ecosystems that use ecological functions like water regulation and water supply to treat wastewater [79]. Therefore, they can produce direct ecosystem services for human wellbeing, such as wastewater treatment, regulation of water flows, air quality regulation and climate regulation. Specific solutions of the CTWs can introduce other specific ecosystem services like recreational and educational use [80,81].

CTWs are valid solutions for secondary and tertiary (finishing) wastewater treatments. Their environmental impact, energy consumption and management costs are significantly reduced compared to other purification systems [82–84]. From an economic point of view, the positioning of the panels in the artificial basin allows the increase of energy produced compared to the ground photovoltaic system because the photovoltaic panels can exploit the solar radiation reflected by the water's surface (albedo) [63,85–89]. Furthermore, the presence of water and vegetation reduces the panels' overheating, which is one of the main causes of efficiency loss of GPV systems, and improves their ecological and cultural value [56,88–90]. The water treated by these plants could be then reused for irrigation purposes in agriculture, urban green areas or others. Furthermore, the treated water is useful for the management of the GPV system, such as for the periodic cleaning of the panels.

Two examples of how GPV systems could be designed to coexist with CTWs without affecting power production are presented. In both cases, the CTWs have been designed following the scheme proposed in Figure 5 and based on a combination of the three currently used systems:

- SFS-h (subsurface flow system—horizontal);
- SFS-v (subsurface flow system—vertical);
- FWS (free water surface).

In SFS-horizontal and vertical, water flows through the filter tank, generally 1 m in depth, filled with gravel and sand, where the roots of the emerging plants are located. The water flows below the surface, with no direct contact with the atmosphere. In SFS-h, the water flows horizontally, while in SFS-v, it percolates vertically. The FWS system reproduces a wetland habitat where the water surface is exposed to the atmosphere [84,91–93]. The medium dimension to guarantee wastewater purification is 4 m^2 for a single inhabitant for the SFS, while for the FWS system, the medium dimension is 25 m^2 for a single inhabitant. Therefore, considering only the SFS, a good solution for 500 to 10,000 inhabitants consists of a total surface of the CTW system of 0.2–0.4 to 4–6 ha. Here, we hypothesise the use of a mixed plant, which has been shown to be the most efficient for wastewater treatment. In this case, the FWS system is used to refine the water leaving the SFS [79,84,92,93].

Considering the GPV systems analysed here as case studies (Figure 4), a possible scheme of hybrid CTW is compatible with the pore space reported in Table 1. For instance, considering the pore space in E and G systems, which is larger than in the other systems (Figure 4 and Table 1), it is possible to realise a CTW for 10,000 inhabitants, while for the other systems, the pore space is compatible with a CTW for 500–2000 equivalent inhabitants.

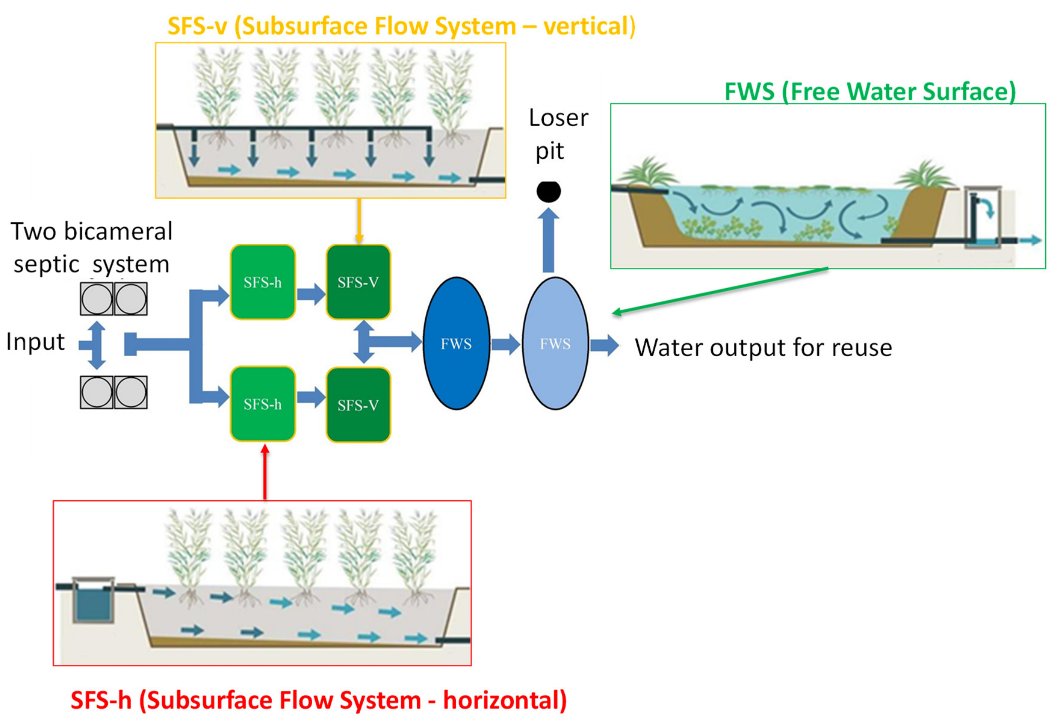

Figure 5. Synthetic scheme of the hypothesised hybrid constructed treatment wetland (CTW; modified from and inspired by [84,91–93]). Loser pit refers to a sink of water from extreme events.

3.3. Step 3. Design of Innovation Green Technological Solutions

Here, potential solutions able to combine GPV systems with CTWs using the "pore space" are presented. Different types of available spaces within the GPV systems are considered as follows (Figure 6):

- Solution 1: Type 1 (SFS: space around the GPV panels) + Type 2 (FWS: pore space and space under the GPV panels);
- Solution 2: Type 1 (SFS: space around and between the GPV panels) + Type 2 (FWS: space around, between and under the GPV panels).

The proposed project idea is applied while maintaining the same technology, energy production capacity and surface of the original GPV systems (full space). In Solution 1, the SFS-h and SFS-v of CTWs are placed in the free space around the panels of the GPV system (Figure 6), while in Solution 2, the SFS-h and SFS-v of CTWs are built around and between the GPV panels (Figure 6). The realisation of FWS is inspired by the floating PV system, where the photovoltaic panels are positioned in the water basin, but in this case, the system is realised in synergy with an ad hoc water basin to produce priority ecosystem services (Type 2).

The proposed solutions mainly differ for vegetation composition in the portion of the CTW characterised by the SFS. In Solution 1, there are no physical constraints on the use of any type of plants because the CTW location does not affect the panel shading. Species of the genera *Cyperus*, *Eleocharis, Glyceria, Juncus, Phalaris, Phragmites, Scirpus and Typha* can be used. The artificial habitats created are useful for both phytoremediation and production of other ecosystem services [78,84]. In Solution 2, the vegetation is located between the panel rows; thus, a careful choice is required to avoid shading. Shrub species with a height between 40 and 100 cm, such as *Juncus spp* or annual and perennial herbaceous plants of commercial value (e.g., *Canna indica or Iris levigata L.*), can be profitably used [68,73,82–84]. This solution is applicable in GPV systems with a high value of the ratio between “pore space” and “full space”. Considering the current spatial arrangement of PV panels, a greater distance between panel rows can be useful to position the vegetation, making better use of the "full space" of the GPV systems for the position of the PV panels without reducing the number of PV panels and, therefore, the power of the system. However, here, we propose some possible solutions to give an idea of the typologies of GI, but these are modulable solutions that can mix different elements. In some portions of the GPV, the site design may include non-CTW plants between the panels that are incorporated to provide additional ecosystem services. Their selection also involves shade considerations, plus their capacity to provide cobenefits for biodiversity and pollination.

The portions of CTWs characterised by the FWS system consist of a water body for phytoremediation where the GPV panels can be located, reproducing a wetland and host aquatic vegetation (hydrophytes and helophytes) that are useful for both urban waste treatment and agricultural purposes. Submerged and floating vegetation can be used as the main vegetation in such systems with no risk of shading. Species of the duckweed family (such as *Spirodela*, *Landoltia*, *Lemna, Wolffiella,* and *Wolffia*) can be adopted as floating hygrophytes [84,91–93]. This solution can be seen as a variant of the topic of “floating PVs” that has been growing in recent years [63], where the water body is designed as an element of CTWs, integrated within farms but never realised in Apulia. There are several technical solutions regarding the position of the GPV panels in water, such as the solutions already used in floating farms [77]. In this case, considering the solar tracking technologies used in some analysed GPV systems and some technologies used in developing agrophotovoltaics [46], where the panels are raised off the ground, we hypothesise that for an FSW system, a potential solution shown in Figure 7 can be explored by companies that use this technology. This can be realised simply by using longer and more resistant support than the current ones for fixing in the ground (Figure 7). This solution, however, can be used with other fixed PV panels. Such a CTW system is designed as an FWS system.

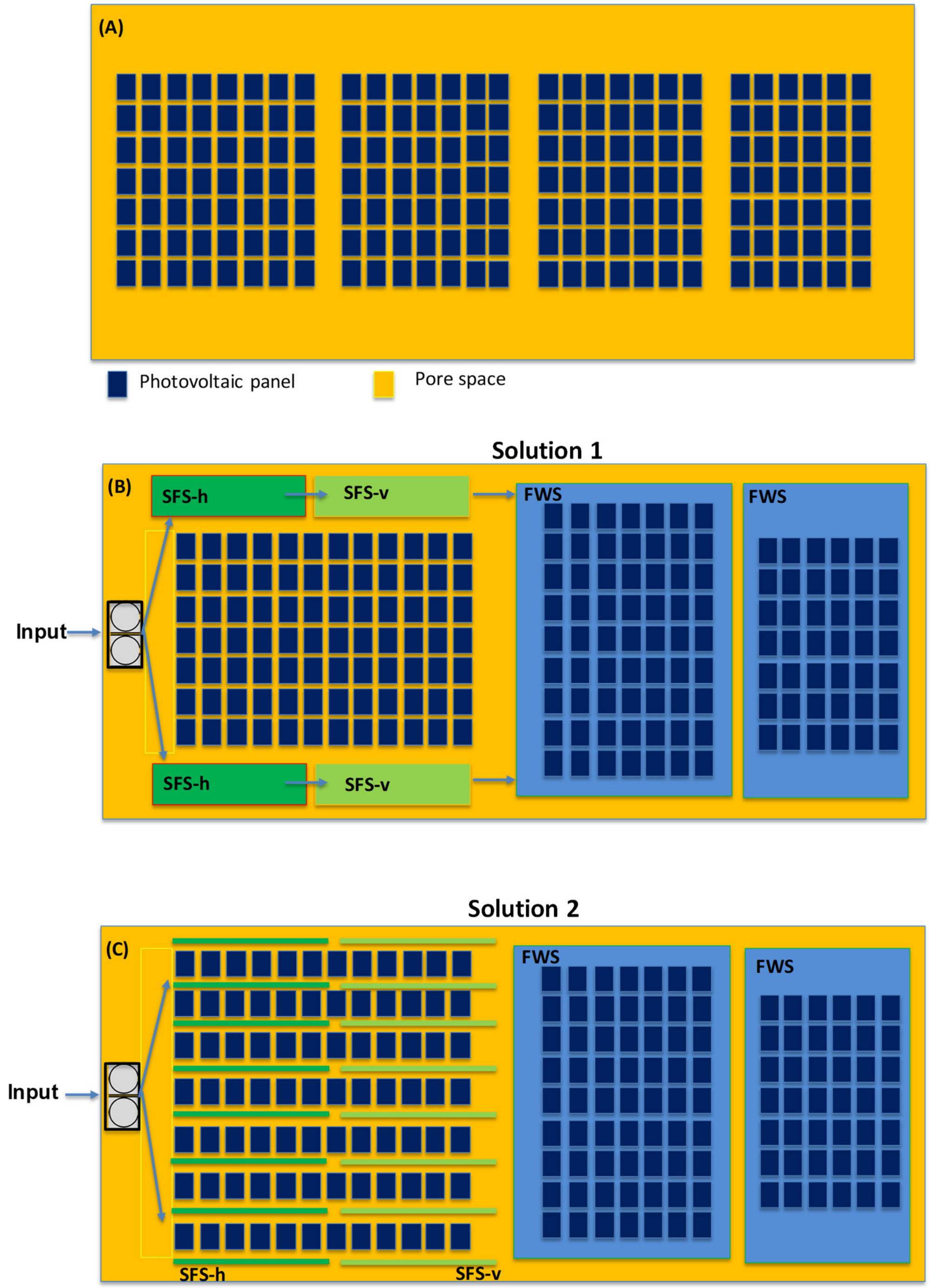

Figure 6. (**A**) Current GPV systems considered as a case study, and proposed Solutions 1 (**B**) and 2 (**C**) integrated with CTWs.

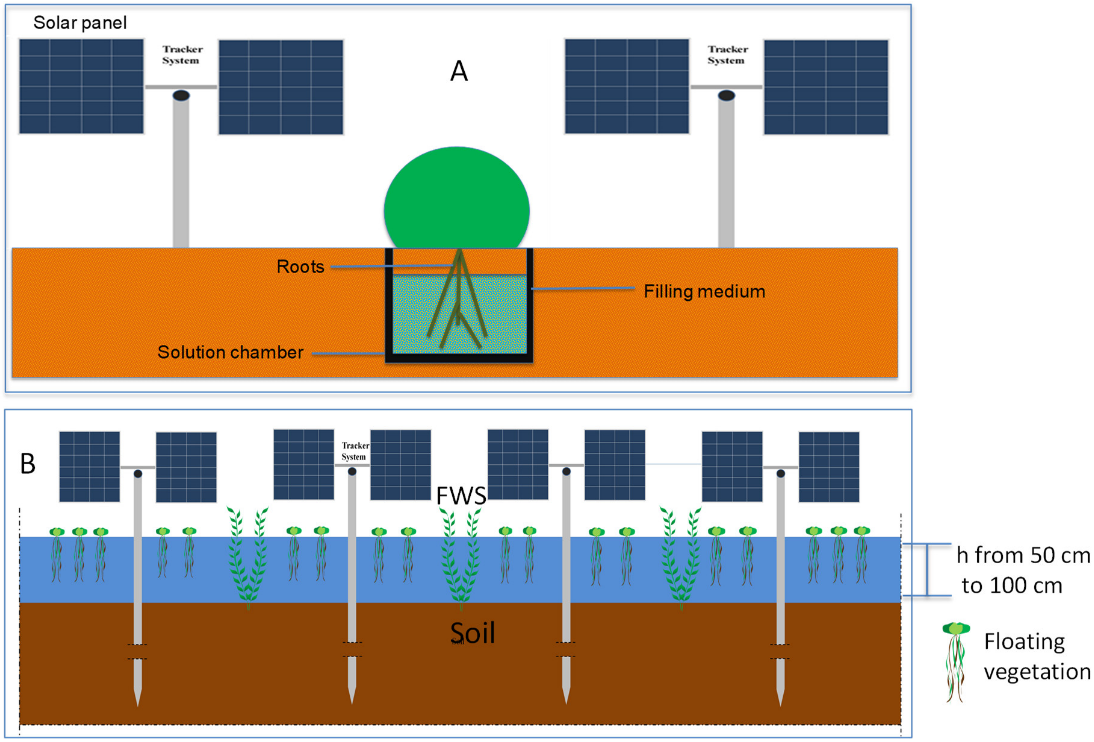

Figure 7. (**A**) Example of solution for the SFS with the vegetation located between the panel rows in one type of the GPV systems analysed; (**B**) schematisation of an example section related to the GPV system integrated with the FWS system, with potential reuse of treated water.

Nevertheless, the system could be easily implemented and modulated to host self-sustainable microscale fish settlements by designing spaces suitable for the introduction of artificial aquatic ecosystems in the CTWs and/or in tanks for breeding freshwater fish species. This kind of implementation might have the dual aim of introducing species that are able to contribute to the environmental balance of the plants and introducing an ecophysiological biomarker component in the system for monitoring biosustainability parameters.

3.4. Step 4. Framework of the Project as Green Infrastructure: Ecological, Social and Economic Potential Externalities

Considering the solutions identified in Figure 6, in this section, the social, ecological, and economic environmental externalities and business benefits are identified, with a focus on the potential ecosystem services that the GI solution can support. Specifically, in Section 3.4.1, an estimation of the potential microclimate variation created by the vegetation in priority ecosystem services is shown; this can have a positive effect on the energy production process. In Section 3.4.2, the evaluation of the increase of ecosystem services in a qualitative way is presented, considering the reference bibliography and social–ecological and economic benefits for the landscape.

3.4.1. Quantification of the Potential Air Temperature Regulation of the CTW Elements

As an example of the benefits provided by the integration of CTWs (to substitute the ruderal vegetation), simulations of temperature variations were performed for two of the analysed GPV systems, A and B (see Figures 4 and 8). These systems were chosen due to the availability of the meteorological data necessary as inputs for the simulations. Both the selected GPV systems are characterised by a flat surface. Solutions 1 and 2, reported in Figure 6, were proposed, creating a new spatial arrangement of GPV panels in synergy with the elements of CTWs reported in Figure 6, keeping the same number of panels and without affecting power production. In these simulations, GPV solutions with solar tracking technologies were considered (Figure 8). In both cases, the CTW system needed about 0.8 ha, with 0.3 ha for the SFS and 0.55 ha for the FWS system in Solution 1, and 0.8 ha for the FSW system in the Solution 2. These CTWs can satisfy about 650/750 inhabitants. In Solution 1, SFS-h and SFS-v were characterised by *Phragmites australis*. In Solution 2, SFS-h and SFS-v were characterised by shrub species such as *Juncus* spp.

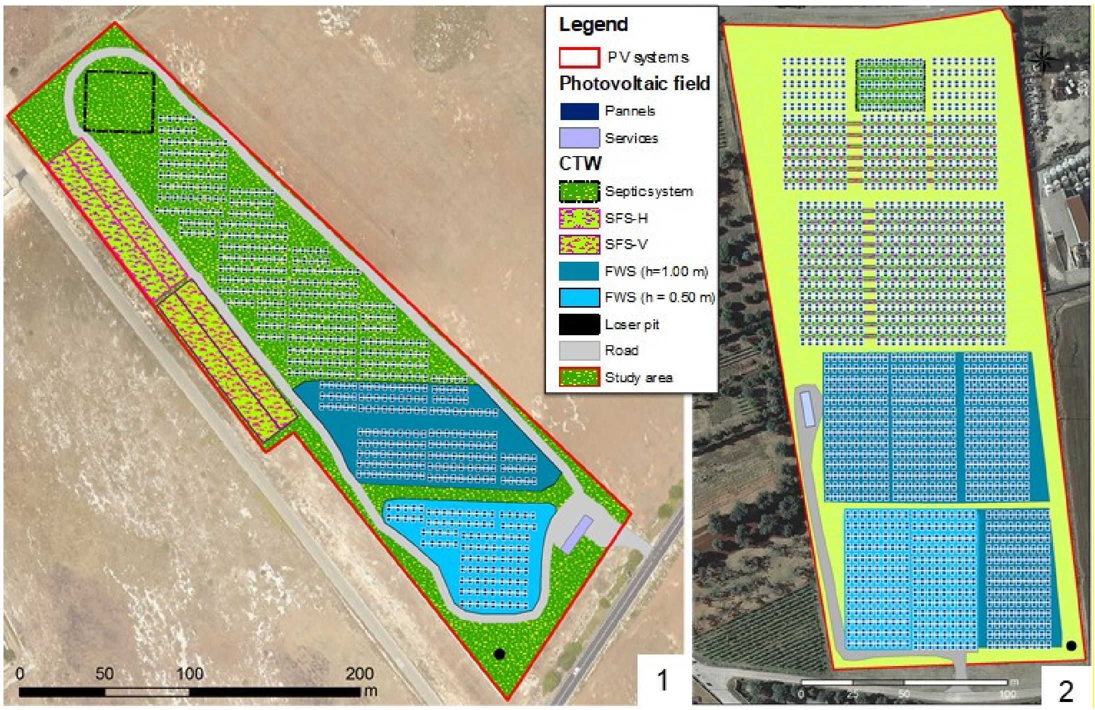

Figure 8. Maps of the two proposed Solutions 1 (in GPV system A) and 2 (in GPV system B), considering the conceptual models in Figure 5.

ENVI-met v4.4 was used to simulate the variation of air temperature (Tair) in the GPV systems, considering the different patterns of vegetation: (i) GPV system with arable land between the panels (intermediate scenario), (ii) GPV system with grasslands between the panels (current scenario), and (iii) GPV system redesigned as GI (design scenario). ENVI-met is a three-dimensional computational fluid dynamics (CFDs) and microclimate model based on the Reynolds-averaged Navier–Stokes (RANS) k-ε model for describing the turbulent flow field that is able to simulate complex surface-vegetation–air interactions in the environment [94]. The ENVI-met application needs two phases: the first consists of modelling the study area by defining the pattern of the vegetation and any other geometrical element present in the different scenarios analysed; in the second phase, meteorological parameters must be defined to characterise the simulation period. The determining factors for the performance of the microclimate are wind speed, incident solar radiation on the module, system installation characteristics and air temperature (Tair). The real dimensions of the areas for Solutions 1 and 2 (see Figure 8 are 300 (x-direction) × 300 (y-direction) × 40 m (z-direction) and 240 (x-direction) × 320 (y-direction) × 40 m (z-direction), respectively. Table 3 summarises the major input variables for ENVI-met simulations (some of them were default values of the model). Specifically, the grid resolution was 2 × 2 × 2 m, with the lowest five cells (close to the ground) having a vertical resolution of 0.4 m. To improve model accuracy and stability, 5 nesting grids were also employed. Hourly air temperature and relative humidity were forced at the model boundary to drive the simulation with meteorological input obtained from an ARPA Puglia 10-m-high meteorological station located not far from the study areas. The day of 7 July 2018 was selected since it was identified as the hottest day in summer, and prevailing wind direction and wind speed in the month of July were chosen. For each case, ENVI-met was run for an 8 h period, starting at 07:00 a.m.

Table 3. Initial and boundary conditions used in ENVI-met simulations of Solutions 1 and 2.

Parameter	Definition	Value
Simulation time	Start Date	7 July 2018
	Start of simulation (h)	07:00
	Total simulation time	8 h
Meteorological conditions	Wind speed	0.9 m/s
	Wind direction	210°
	Temperature of atmosphere (forced)	Daily profile (7 July 2018)
	Relative humidity (%) (forced)	Daily profile (7 July 2018)
Solar radiation and clouds	Adjustment factor for solar radiation (Lecce)	0.81
	Cover of low clouds (octas)	1.00 (clear sky)
	Cover of medium clouds	0.00 (clear sky)
	Cover of high clouds	0.00 (clear sky)
Soil	initial temperature (K) and relative humidity (%) of upper layer 0–0.2 m	293—50 (default values)
	initial temperature (K) and relative humidity (%) of middle layer 0.2–0.5 m	293—60 (default values)
	initial temperature (K) and relative humidity (%) of deep layer below 0.5 m	293—60 (default values)
Computational domain and grid	Grid cells (x,y,z)	150 × 150 × 20 (area A) 120 × 160 × 20 (area B)
	δx × δy × δz	2 × 2 × 2 m (equidistant: 5 cells close to the ground)
	Nesting grids	5
	Boundary conditions	Cyclic

Results show that there is no difference in Tair between the first two scenarios (arable land and grasslands). The main temperature differences occur with the introduction of CTW. Specifically, in Solution 1, the higher variation of Tair occurs in the design scenario, mainly in the FWS area, with effects in the surrounding areas as well. The maximum difference recorded is about 1 °C (Figure 9). In Solution 2, the variation of Tair in all areas, and the main effect in the area where the vegetation is introduced (SFS-v and SFS-h areas) is recorded. The maximum difference is about 2 °C (Figure 9).

Therefore, if the effect of the water bodies on the air temperature in the photovoltaic system is known [63,85,89], this study opens new scenarios about the effects of the presence of vegetation between and around the photovoltaic panels. However, it should be noted that for the sake of simplification, the analysis has been carried out without considering the presence of panels and their arrangement difference between the simulations, which is left to future evaluations. However, the intent here is to show the temperature variation induced by the presence of ruderal vegetation and CTW in order to analyse the general ability of CTWs to support microclimate regulation. We expect that similar qualitative results may be obtained in the presence of panels, which is hard to reproduce with the chosen model. On the other hand, the model is one of the most widely employed ones, and it is considered appropriate to evaluate the general effect of vegetation scenarios, as performed in this study. It is expected that the presence of the panels would enhance the temperature differences between the scenarios, mainly in Scenario 2, where the GPV panels are less dense than the arrangement of the current GPV panels. These differences could increase in the areas with higher extreme temperatures, where the effects of ecosystem mitigations could be more influential.

Furthermore, the simulations refer to low GPV systems of low extension, and thus the effect on temperature mitigation could be amplified, considering a bigger GPV system where there is a possibility of creating a sort of heat island effect, like what happens in cities.

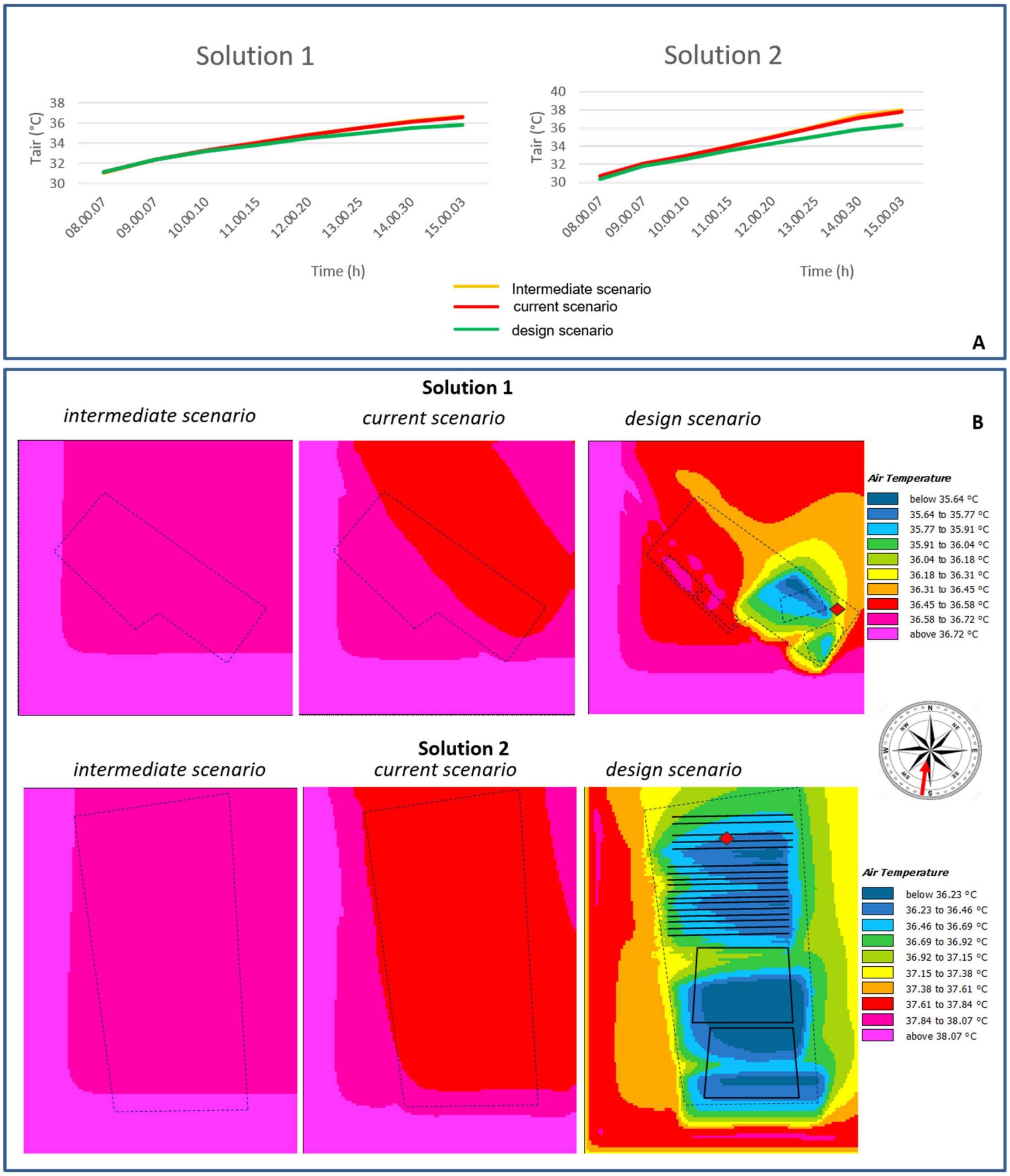

Figure 9. Simulation of temperature regulation considering CTW scenarios reported in Figure 8: (**A**) Air temperature (Tair) hourly profiles for solution 1 and solution 2; (**B**) Spatial characterization of air temperature (Tair) at 15:00 for solution 1 and solution 2.

3.4.2. A New Vision of GPV Systems as Green Infrastructure

GPV systems designed as GI can represent a green infrastructure able to directly provide ecosystem services like microclimate regulation, water regulation, wastewater treatment and water supply, and also indirect ecosystem services supporting social and economic human benefits [11,12]

In the previous section, we estimated that the combination of natural solutions developed can produce up to 2 °C of variation of temperature. In terms of water depuration, these solutions (Figure

8) can treat from 130 to 150 m^3 of wastewater per day, considering the inhabitants of the reference context and a specific volume of wastewater discharge that in the field of purification planning, is usually assumed to be 0.2 m^3/inhabitant per day. Therefore, in one year, these natural solutions can support water treatment ecosystem services from 47,450 to 54,750 m^3 [95], of course, these data are only indicative. The water purified can be reused for human use, such as agricultural and industrial activities, but also for the companies' processes because the water can be used to clean the photovoltaic panels.

However, GI is linked to the concept of serendipity, and hence, the possibility of such interventions to obtain benefits that were not planned in the initial design goal, without the need of quantifying or evaluating them in consideration of future technologies. Table 4 summarises the potential direct and indirect ecosystem services which can be achieved when moving from the current ruderal vegetation of GPV systems analysed to the new design project using the economics of ecosystems and biodiversity classification [96,97].

The CTWs integrated with GPV systems can develop other direct ecosystem services linked with habitat support. As verified in the CTW in the town of Melendugno (the municipality located close to the GPV systems analysed here), the CTW can become a habitat that is able to sustain local and migratory species despite no intentional plan to do so [78]. Therefore, GPV systems integrated with CTWs can foster new ecological elements of the landscape that can strengthen biodiversity in an agricultural matrix characterised by monocultures, such as arable land and olive groves, supporting the ecological network, for instance, through wildlife corridors or stepping-stones and ecobridges between different natural elements of the landscape [31]. Mainly, GI can represent the "sink" of biodiversity, and therefore, an area in the agricultural matrix where the biodiversity can find refuge and develop without the risk of being threatened by anthropic activities. At the same time, GI can constitute a "source" of biodiversity and, therefore, an element of the landscape where the biodiversity can sprawl and recolonise natural areas (Figure 10a). Taking as a reference the study carried out for the CTW of Melendugno [78], located near one of the plants analysed, it is possible to hypothesise that the realisation of CTWs integrated with GPV systems would provide ancillary ecological benefits, including wildlife habitat provision, favouring the presence of species of high conservation value that are strongly at risk, like birds, due to the simplification of land-use forms and the resulting fade of habitats suitable for reproduction [78,84] (Figure 10b). However, in this study, we planned GI without focusing on specific target biodiversity species because we have focused mainly on water support, wastewater treatment, microclimate mitigation, and functional biodiversity for supporting these priority ecosystem services. The integration of GPV systems in the ecological network can be realised in different ways and for different aims. For instance, the GI can be realised to support specific target biodiversity like pollinating insects, and in this case, the design vegetation will be functional to realise the sustainment of these animals, with plants supporting honey production [20,21]. Therefore, it can be possible to sustain other ecosystem services, such as pollination, which constitutes an important ecosystem service linked with agricultural food production [78].

At the legislation level, the realisation of GPV systems like GI provides the opportunity to strengthen the European Natura 2000 ecological network, with benefits on multiple scales in biodiversity enhancement (Habitat Directive 92/43/CEE and Directive 2009/147/EC; Figure 8). Moreover, this approach is coherent with the new biodiversity strategy for 2030 that promotes "win–win solutions for energy generation", such as solar-panel farms that provide biodiversity-friendly soil cover [40].

Table 4. Ecological processes and functions linked to the production of good and services identified for CTWs integrated with the GPV systems considered. A qualitative scale, from low (+) to high (+++), is employed to indicate an increasing capacity to support ecosystem services [94–98].

Functions		Ecosystem Services	CTW	References
Regulation functions (Maintenance of essential ecological processes and life support systems)	Gas regulation	Maintenance of (good) air quality Influence on climate	+++	[10,75,78,99–101]
	Climate regulation	Maintenance of a favorable climate (temp., precipitation, etc.) for human habitation, health, cultivation.	+++	[10,75,80,82,99–101]
			up to 2 °C decrease	estimation from the simulations performed (Figure 9)
	Disturbance prevention	Storm protection Flood prevention (e.g., by wetlands and forests)	+++	[10,75,80 82,99–101]
	Water regulation	Drainage and natural irrigation	+++	[10,75,80,82]
	Water supply	Provision of water for consumptive use (e.g., drinking, irrigation and industrial use)	+++	[10,75,80,82]
			From 47,450 m^3 to 54,750 m^3	estimation from the solutions in Figure 8
	Nutrient regulation	Maintenance of healthy soils and productive ecosystems	++	[10,75,80,82]
	Wastewater treatment	Pollution control/detoxification Filtering of dust particles (air quality) Abatement of noise pollution	+++	[10,75,78,80,82]
			From 47,450 m^3 to 54,750 m^3	estimation from the solutions in Figure 8
	Pollination	Pollination of wild plant species Pollination of crops.	+	[10,75,80,84]
Habitat functions (Providing habitat (suitable living space) for wild plant and animal species)	Refugium function	Maintenance of biological and genetic diversity (and, thus, the basis for many other functions)	+++	[10,75,78,84]
	Nursery function	Maintenance of commercially harvested species	++	[10,75,78,84]
Production functions (Provision of natural resources)	Food	Hunting, game, fruits, etc. Small-scale subsistence	+	[10,75,78,84]
	Raw materials	Building and Manufacturing (e.g., lumber) Fuel and energy (e.g., fuel wood)	+++	[10,75,78,84]
Information functions (Providing opportunities for cognitive development)	Aesthetic information	Enjoyment of scenery (scenic roads, housing, etc.)	++	[10,75,78,81]
	Science and education	Use of natural systems for school excursions, etc. Use of nature for scientific research	++	[10,75,78,81]
Carrier functions (Providing a suitable substrate or medium for human activities and infrastructure)	Habitation	Living space (ranging from small settlements to urban areas)	+	[10,75,78,81]

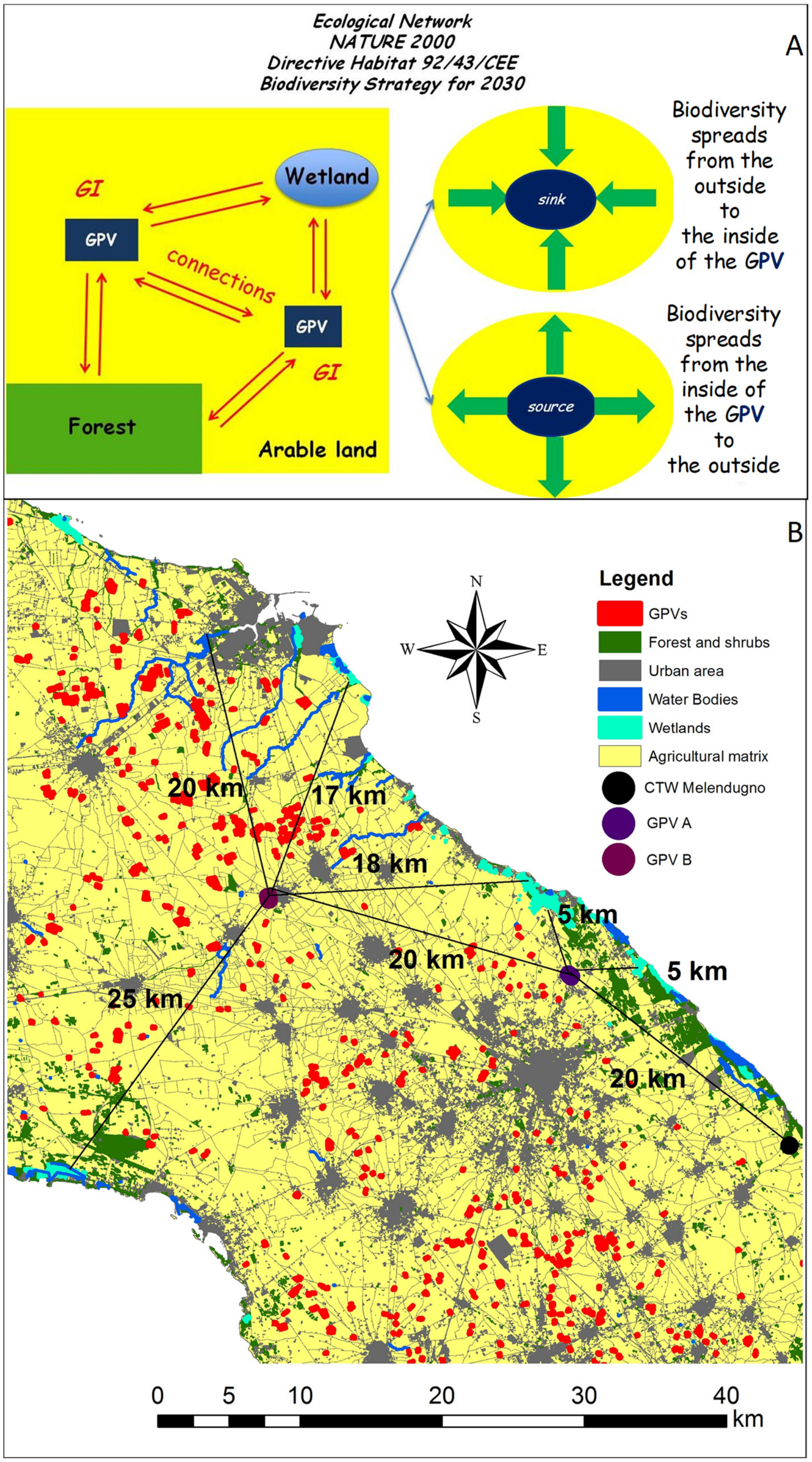

Figure 10. GPV systems thought as GI, representing an ecological functional element of the landscape: (**A**) Conceptual scheme of the ecological network considering GPV systems like GI; (**B**) potential ecological network that can be realised in the landscape of reference, considering the conversion of GPV systems A and B (Table 2 and Figure 4) into CTWs.

The ecosystem services developed from the planned GI can stimulate new business activities. For example, the vegetation material derived from CTWs can be used to produce building material or, in general, other cellulose-based products like textiles, ropes and paper. Duckweed vegetation (*Lemna minor L.*), which can be used for water purification, has been proposed as a supplement to animal feed to complementary diet and increase animal growth, as well as for phytoremediation of contaminated water bodies. The amount of starch produced per ha by *Lemna minor L.*, for example, is up to five times higher than corn, suggesting that this novel culture may be cost-effective and sustainable for bioethanol production, the related land-use change, and the resulting greenhouse gas (GHG) emissions [86–88,101,102]. Therefore, a new biofuel production chain linked to such GPV systems could arguably be created [103–105].

This typology of solutions can be flexible and can be used for different applications. For instance, the combination of GPV with CTW can represent a solution for industry sectors, such as metallurgical companies that need treatment of the water of the metal components. In this case, the vegetations of CTWs can be constituted by cannabis light, which is able to absorb metals. Indeed, duckweed has been demonstrated to be a good accumulator of cadmium, selenium, and copper, a moderate accumulator of chromium, and a poor accumulator of nickel and lead [106]. They are also capable of uptaking and transforming phenols, pesticides, and many other environmental organic and inorganic pollutants. These companies have the possibility of supporting energy and water needs, with the possibility of reducing pollution emissions [107,108].

4. Discussion

The European Union has defined GI planning as a successfully tested tool to provide environmental, economic and social benefits through natural solutions. In many cases, it can reduce dependence on "grey" infrastructure, which can be damaging to the environment and biodiversity and often more expensive to build and maintain [109].

In this sense, the framework developed here can support the ecological design of GPV systems, creating shared value between the energy companies and the local population by increasing the carrying capacity of the urban system. The ecological functions will sustain energy production and water supply and reduce the ecological footprint of the urban system by using urban primary-function high-impact technology or by addressing global markets (in this case, wastewater treatment).

Moreover, in the solutions developed, a GPV system is not only an energy plant producing energy with no CO_2 emission. As the wetland area has a strong capacity to stock CO_2 [110], CTWs integrated with GPV systems can be considered a sink of CO_2 and an important landscape element to mitigate climate change both at local and global levels, increasing the efficiency of renewable energy strategies to reduce global changes [99,110–112]. CTWs in pore spaces of GPV systems can also mitigate air temperature; this represents an important ecosystem service that can be directly important for GPV energy efficiency, improving the amount of energy produced (due to temperature reduction around the panels), with positive effects on the current–voltage of the panels themselves [56,86,90]. Such an approach may promote more sustainable access to water and energy while protecting biodiversity and ecosystem services, as requested by the sustainable development goals for people and the planet [113–115].

This work represents a result of knowledge integration between different disciplines with different approaches, namely, contributions by an expert in energetic industrial and engineering sectors and also an expert in landscape planning and environmental fields. Moreover, this work includes experiences of people that have worked in applied projects and land-use transformation and people that have worked in research fields. Therefore, the result can be easy, but it is not trivial. More disciplines are needed to implement the quantification of the effect of the project on human wellbeing. This will be a point for the future development of this work.

In this direction, an important contribution can be provided by scientific sectors that have to help to translate the theoretical approach of ecosystem services into project solutions. At the moment, research is generally motivated by targeting the most intellectually novel and stimulating research questions based on scientific literature that are often not tuned to finding solutions to society's most pressing problems. As a consequence, there is a gap between the needs and expectations of society for the application of research knowledge, leaving the translation of research to applications on social and ecological issues to others that do not have this knowledge [116].

In this context, this study wants to represent a framework that suggests knowledge transfer from the scientific world to the public and private operators managing the territory, suggesting land-use projects to harmonise economic development and biodiversity enhancement.

Specifically, GPVs integrated with CTWs should aim to harmonise private economic interests with public, social and environmental ones, developing partnerships where private enterprises obtain administrative support to invest in productive projects fostering positive externalities and useful services for the territory. For example, in this case, the public administration could propose a public tender addressed to private individuals for the construction of the wastewater plant and management at no cost for the administration. Such an initiative would make it possible to recover the proven investment costs through the sale of the energy produced and secondary activities that can be developed. On its part, the private sector could promote a project on renewable energies, also considering which ecological and social benefits can be developed in the project as a service to the local community to obtain support from the public administration. GI can be an alternative to royalties that, many times, companies have to pay the municipality for the realisation of the project. Therefore, companies could offer social and ecological services, and the economic costs for the integration of the different components that make up these ecological services, for example, wastewater treatment, can be paid off through greater energy production and from the avoided cost of the royalties. Moreover, applying both systems in an integrated way in the same portion of the land helps to pay off land acquisition costs, avoiding land consumption by creating multifunctional land use according to national and international goals on the reduction of land use [40].

These types of design approaches could be an integral part of the Strategic Environmental Assessment (SEA: Directive 2001/42/EC) and Environmental Impact Assessment (EIA: 85/337/EC and following modifications), tools aimed at evaluating environmental impacts on plans and projects in order to promote the sustainable development of human activities. An important part in any SEA and EIA is represented by the mitigation measures, i.e., actions needed to reduce the expected adverse environmental impacts. The GPV system plans and projects need SEA and EIA process approval for their realisation. Consequently, if the ecosystem services are not an intrinsic concept in the design of GPVs, they can be an integrated concept in SEA and EIA processes to guarantee human wellbeing [117]. Therefore, it could be the decision-makers' role to promote, in this phase, the integration of the project to green infrastructure solutions able to create shared value.

The proposed project can be mainly applied to regions where the urgent need of generating energy from renewable sources has caused evident changes of landscape and land use as a result of the high power installed, fostered by specific local laws that have focused more on production than on landscape preservation issues. Such projects can find usefulness and economic convenience in polluted abandoned sites located near urban areas, often called "brownfield sites", where reuse or land use transformation must also include operations and costs for land reclamation. It is often a matter of polluted sites included in urban areas or suburbs, already equipped with all urbanisation works (electricity, water, gas, sewage system) and close to transport lines and connections. In this case, the framework can be useful to develop the GPV system like GI within an integrated environmental design that involves the redevelopment of such brownfields areas, with the aim of creating new ecological, economic and social potential functions and simultaneously removing pollutants. The phenomenon of brownfield sites in urban areas is mainly linked to transformations of the economic system and industrial process and the evolution of social sensibility and culture towards the issues of life's quality and environmental aspects [118–120].

5. Conclusions

This work aims to emphasise the possibility of implementing sustainable renewable energy projects with sustainable actions that do not constitute a simple additional cost for companies, but rather, an investment and an opportunity for innovative development in the business and social–ecological context.

Ecosystem services represent a key element for the design of GPV systems capable of creating shared value because they create a direct link between biophysical structures and ecological functions with human wellbeing in mind. In this way, GI represents a new approach to designing land use transformation, including natural-based solutions to improve efficiency in the use of natural resources with effects on social–ecological and economic aspects of the landscape and companies.

In this context, this study wants to produce a framework that suggests a knowledge transfer from the scientific world to public and private operators managing the territory, suggesting land-use projects of GPV systems to harmonise economic development and biodiversity enhancement. In this sense, a cultural transition in the design of renewable energy plants from a mono- or interdisciplinary approach (which, many times, has led to a “copy and paste” in the plant’s design) to a transdisciplinary approach is foreseen, where every contribution is used to produce a holistic vision in the project involving both private and public sectors.

Therefore, in businesses that produce a land-use change for energy production, we propose a CSV to transfer the concept of ecosystem services in the e-commerce model to a new generation of GPV systems that bring about positive environmental externalities, increasing energy income and company advantage. In this way, the practical application of the conceptual framework will imply that

- The realisation of GPV systems as GI does not represent a simple mitigation measure, but a development strategy that administrators (local, regional and national) can employ to create added ecological and socioeconomic values in the urban context.
- Ecosystem functions are reinterpreted as supporting technology services to produce innovative thinking as the capacity to do the same things in different ways.

We think that the philosophy of GI, through the input of renewable energy production, can push private individuals to indirectly invest in public services and strategies that public administrations are not capable of putting in practice due to the economic crisis.

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